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FOREST MAPPING OF THE NORTHERN HEMISPHERE WITH SPACEBORNE RADAR

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ABSTRACT

The use of spaceborne Synthetic Aperture Radar (SAR) is fundamental for forest mapping and monitoring for the northern hemisphere because of non-adequate solar illumination for most of the year around and the sensitivity of the radar observables to forest structure. Past and current spaceborne SAR missions have not been designed specifically for forest monitoring. Nonetheless, in recent years a number of investigations based on the extensive datasets of archived radar images have shown that large-scale applications ranging from forest cover mapping to retrieval of forest growing stock volume / stem volume are feasible. In this paper we present an overview of results on forest mapping in Eurasia and Northern America using SAR backscatter and interferometric SAR coherence images acquired by the ERS, Envisat ASAR, JERS-1 and ALOS PALSAR sensors.

1. INTRODUCTION

Spaceborne Earth Observation (EO) has been acknowledged in recent years as fundamental component for monitoring the Earth System [1]. Understanding the Earth System in the context of climate change requires frequent and accurate measurements of forest extent and forest status at the global scale, an impossible task to be tackled with traditional survey methods. Images acquired by optical sensors have been integrated in algorithms targeting the retrieval of forest parameters. Such products (e.g. the fraction of photosintetically active radiation, phenology or fractional land cover) are available at the global scale, with high temporal resolution and are becoming established tools in climate models. While optical images are suitable for retrieving forest properties regarding phenology and photosynthesis, they do not capture information about the structure of trees. In this respect, observations with synthetic aperture radar (SAR) are appealing since microwaves penetrate to a certain extent the forest canopy and the scattered signal is therefore related to physical and structural properties of the forest. The main drawback of SAR so far has been that past and currently orbiting radar satellites operate at frequencies that are generally considered either unsuitable or at the limit for deriving reliable information about carbon stocks. ERS, ENVISAT, Radarsat and TerraSAR-X (C- and X-band) are generally discarded when it comes to deciding which EO tool could be adequate for forest cover monitoring and forest biomass mapping. JERS-1 and ALOS PALSAR (L-band) data are primarily seen as information source on forest cover.

In this paper we aim at demonstrating that 20 years of SAR observations can be exploited to map forests of the northern hemisphere even with high frequency radar to a degree that was previously considered unfeasible. The key is the availability of multiple observations of both SAR intensity and interferometric SAR coherence, which has allowed at an early stage of research to deeply understand the signatures of the radar observables. These investigations have paved the way to setting up algorithms that optimally exploit the characteristics of the measurements in order to extract information beyond what is considered feasible at a first glance.

Section 2 provides a summary on the signatures of radar observables in boreal and temperate forests and methods proposed in literature for forest classification and parameters retrieval. Sections 3 and 4 are then dedicated to a specific mapping and/or monitoring theme, i.e. forest cover mapping and retrieval of forest growing stock volume. An outlook on future investigations and possibilities with current and upcoming spaceborne radar sensors is presented in Section 5.

2. BACKGROUND

Forests are a complex medium characterized by a volume with a certain thickness in which several objects are distributed and an underlying surface, i.e. the forest floor. Radar frequency, look geometry and polarization determine the objects that scatter the incoming microwaves. In addition, the dielectric properties of objects further affect the backscattered signal. Therefore, explanation of the signal scattered back from a forest requires that (i) radar configuration, (ii) forest properties, i.e. structure, and (iii) environmental conditions are all taken into account. This is also the key to set up adequate algorithms for forest-related studies using SAR.

Past and present spaceborne SAR operate in a range of wavelengths between 3-5 cm (X- and C-band) and 23 cm (L-band). The longer wavelength implies larger degree of penetration of the microwaves into the forest canopy. For X- and C-band the largest proportion to the scattering has been attributed to objects within the first few meters of the canopy (leaves, needles, small branches). At L-band the backscatter originates primarily within the canopy at the level of the main branches. The sensitivity to forest structural parameters is therefore stronger at lower frequency.

The strong attenuation of the microwaves in the forest canopy at high frequency also implies that the total forest backscatter is only marginally affected by the backscattering from the forest floor. A slightly larger contribution takes place at L-band. Double-bounce and multiple reflections can be considered negligible in most cases. The contribution from the forest floor is instead significant in sparse or regenerating forest.

Given a certain frequency, the proportion of scattering originating in the canopy and from the forest floor furthermore depends on look angle and polarization. For shallower angles the path travelled by the microwaves in the canopy is longer and the proportion of signal scattered from the forest floor decreases. Hence, shallower angles are characterized by an increased sensitivity of the received signal to structural parameters. Targets characterized by volume scattering present stronger depolarization effects compared to surface scattering. Cross-polarized backscatter therefore contains more information on forest structure than co-polarized backscatter.

The interpretation of the signal scattered from a forest cannot disregard the dielectric properties of vegetation and forest floor, and the environmental conditions at the time of image acquisition. The sensitivity depends however on the radar frequency and to a certain extent, on the polarization. Sub-zero temperatures or very dry unfrozen conditions increase the transparency of a canopy, thus implying a different scattering scenario. Similarly, the wet or dry conditions of the forest floor and the presence of snow layer can alter the scattering mechanism significantly, primarily at high frequency.

The repeated acquisitions of SAR images from the same orbital track allows the generation of interferometric SAR (InSAR) images as well. Interpretation of the interferometric coherence, i.e. the correlation between the two images, requires taking into account the coherent aspects of the backscattered signal, which implies bearing in mind the (i) the temporal stability of the scattering scenario between the two acquisitions and (ii) the interferometric baseline. For current and past spaceborne InSAR systems, the temporal aspect is by far more relevant. Temporal decorrelation sets in more rapidly at higher frequency because of the higher temporal instability of the scatterers. The interferometric baseline causes volume decorrelation, thus being more relevant in case of stronger penetration of the microwaves in the canopy (e.g. at L-band under unfrozen conditions).

The main signatures of the forest backscattered intensity and interferometric coherence are summarized below in terms of operating frequency on the basis of available spaceborne SAR datasets. It should be noticed that for L-band interferometric coherence the overview is limited to the case of long repeat-pass cases (at least 44 days) since only very few examples of short-time repeat-pass interferometry are available [2].

- C-band backscatter
  - Predominant contribution from canopy (top);
  - Strong contribution of forest floor geometric and dielectric properties;
  - Strong sensitivity to environmental conditions;
  - Increased (however still limited) sensitivity to forest structural parameters for frozen conditions, at HV polarization and for shallower look angles.

- L-band backscatter
  - Predominant scattering from within canopy objects (volume scattering);
  - Weak contribution of forest floor geometric and dielectric properties;
  - Seasonal sensitivity to environmental conditions;
  - Compared to C-band, stronger sensitivity to forest structural parameters.
  - Increased sensitivity for unfrozen conditions, at HV polarization and for shallower look angles.

- C-band interferometric coherence
  - Stronger temporal decorrelation effects in dense forest than for unvegetated areas for stable environmental conditions;
  - Overall strong temporal decorrelation for unstable environmental conditions;
  - Sensitivity of volume decorrelation to length of baseline;
  - Increased sensitivity to forest structural parameters under stable environmental conditions (frozen or dry);
  - Further increase of sensitivity for specific baselines (e.g. 200-250 m in the case of ERS);
  - Much stronger sensitivity to forest parameters compared to the backscatter intensity.

- L-band interferometric coherence
  - As for C-band stronger temporal decorrelation effects in dense forest than for unvegetated areas (mostly);
  - Sensitivity of volume decorrelation to length of baseline;
  - Sensitivity to forest structural parameters depending on the degree of temporal instability of the scatterers;
  - Equally high sensitivity of coherence and HV-backscatter intensity to forest parameters.

While these results indicate that L-band data are most suitable for forest cover mapping and forest parameter retrieval, the development of related algorithms for large-scale applications has to take into account the availability of SAR datasets as well. The ERS mission lasts since 1991 and has produced an enormous archive of SAR images. Multi-temporal approaches were found to increase the usefulness of C-band backscatter datasets for forest mapping [3] and retrieval of forest parameters [4]. During the ERS-1/2 tandem mission in 1995-1999 several image pairs with one-day temporal separation have been acquired, boosting the use of coherence in forest-related studies. Simple classification approaches and relatively straightforward retrieval techniques provided results with high accuracy [5]. Nonetheless, the coverage of the northern hemisphere is only partial. Although the Envisat mission lasting since 2002 can be seen as follow-up of the ERS mission, it misses the short-term interferometric component (repeat-pass of 35 days). Systematic and large-scale acquisitions take place in the low-resolution ScanSAR mode only (150 m and 500 m). The very high density of observations within a short time period has revived the use of the multi-temporal approaches developed for ERS images [6]. With data from the JERS-1 mission (1992-1998), it was primarily proven that (i) large-scale forest mapping with radar is feasible [7], (ii) retrieval of forest parameters is possible with a limited set of measurements [8] and (iii) coherence is exploitable despite the long temporal baseline [9]. The legacy of the JERS-1 mission has served to set up the observation strategy of the ALOS PALSAR mission. This can be considered as the currently most suitable system for forest observations with radar, thanks also to the polarimetric capability. The PALSAR mission however misses in part the multi-temporal aspect, which we believe is the key for deriving more detailed information on forests with respect to one or a small number of observations.

3. FOREST COVER MAPPING

The application of SAR data in forestry that is closest to operational level is forest cover mapping, i.e. the discrimination between several types of vegetation growth conditions at a given time. Long wavelengths are preferred because of the stronger sensitivity to forest cover and the more predictable effects of seasonal conditions on the observations.

Within the GMES project GSE Forest Monitoring a total area of 200,000 km² has been mapped in the Irkutsk Oblast, Central Siberia, over three years (2006-2009). During the first two years Envisat ASAR Alternating Polarization (AP) images have been used. It was found, that during spring time, when snowmelt takes place, the best backscatter contrast between forest and non-forest areas was obtained. For the delineation of forest and non-forest classes, the SAR data was classified on an object level. The classification itself was supervised and utilized the nearest neighbour approach. Still, a large amount of post-processing effort was required as by means of a few C-band images clear separation of forest and non-forest is not feasible. With the launch of ALOS PALSAR in 2006 more suitable data became available and the mapping could be improved. Reliable separation between forest and non-forest using a limited number of images could be achieved. The implementation of winter-coherence and summer intensities led to an almost perfect separability of forest and non-forest, including detection of recent forest cover changes due to clear-cutting. Reference [10] ascertained an average separability between forestry related classes of 0.95 (normalized Jefferies–Matusita distance; 1 = maximum separability). Fig. 1 shows a color composite of ALOS PALSAR data (R: HH, G: HV, B: coherence) and the corresponding forest cover map.

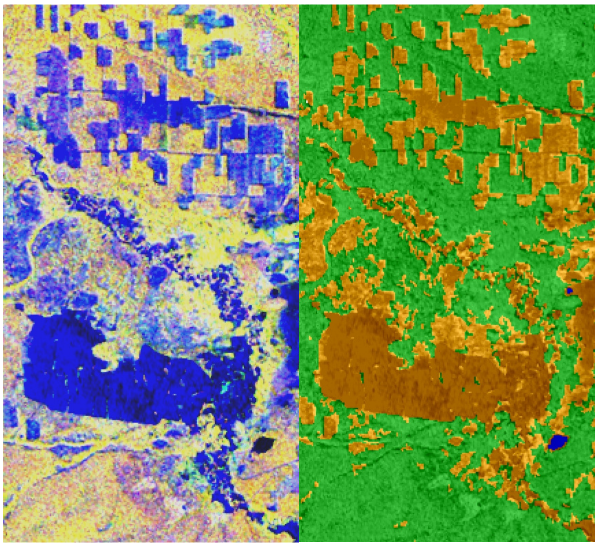

Figure 1. ALOS PALSAR color composite (left) and corresponding forest cover map (green: forest, brown: non-forest) for a 240 km² area in Siberia.

Intensive exploration of ALOS PALSAR data for forest cover mapping in the boreal zone is the topic of an ongoing activity in the framework of the Kyoto and Carbon Initiative [11]. Again, interferometric coherence and L-band backscatter is utilized. This time however, due to the very large areal extent, the classification procedure needs to be fully automated. This will be achieved by means of the implementation of multitemporal data. Multi-temporal metrics contain additional information such as the backscatter variability and allow for threshold based classification strategies. First results based on C-band were characterized a classification accuracy above 95% [12].

Detection of forest cover changes, i.e. monitoring the dynamics of forest cover, requires images that not only present certain sensitivity of the observable to forest cover but are also characterized by a limited effect of environmental conditions on the observable. In this respect L-band data are most appealing. In [13] it was shown that clear-cut detection in European and Siberian forests is possible with HH-backscatter acquired by the JERS-1 SAR sensor. The JERS winter coherence was instead proved to be effective to detect clear-cuts under frozen conditions in Siberia [14]. The polarimetric feature of ALOS PALSAR enables an improvement with respect to JERS because of the strong sensitivity of the cross-polarized backscatter to forest density [15]. Clear-cut detection in Swedish forest with a simple thresholding algorithm was found to perform well, with a detection accuracy of about 90% [16].

4. RETRIEVAL OF FOREST GSV

Retrieval of forest GSV exploits the capability of microwaves to penetrate into the forest canopy. While in literature encouraging results from several experiments have been reported, still the application of SAR data to retrieve GSV has not had a major breakthrough, primarily because the spaceborne SAR data available so far has not met the requirements of high accuracy and high resolution demanded by forest inventories. When however targeting a different user community such as the carbon community it is believed that the contribution of SAR data to estimating carbon stocks can be substantial.

At C-band the performance of the interferometric coherence was found to be significantly better compared to the backscatter [17, 18]. At L-band backscatter data were found to provide rather accurate information on GSV [8, 19, 20]. The L-band coherence has been investigated [9, 21, 22] showing clear sensitivity to GSV. Besides [23] who reported relative errors between 33% and 46% for multi-temporal JERS-1 coherence data, the capability of spaceborne L-band interferometry is yet to be assessed. It is however feared that the long repeat-pass for the available datasets undermines the applicability of the coherence.

The EC-funded SIBERIA Project at the beginning of this decade was a pioneer in using interferometric SAR data for large-scale forest mapping. In this context it was demonstrated that with a single ERS-1/2 tandem coherence dataset and a single JERS backscatter dataset it is possible to derive four classes of forest growing stock volume with 90% accuracy over a 10^6 km^2 area in Central Siberia [24, 25]. In [26] it was demonstrated that the spatial details in the map of Siberian forests shown in Fig. 2 can significantly improve the estimation of carbon with respect to existing products of the same kind.

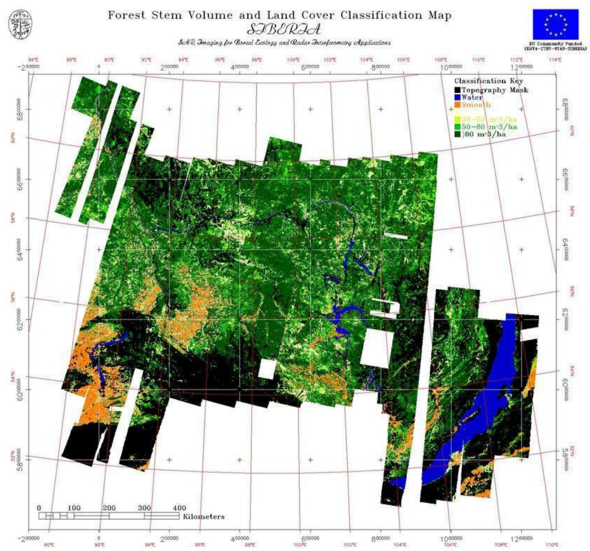

Figure 2. Map of four GSV classes, water bodies and smooth surfaces obtained with ERS-1/2 tandem coherence and JERS-1 backscatter for a 1 million km^2 area in Central Siberia.

Almost simultaneously to the SIBERIA project, even if to a smaller extent, a map of continuous values of forest stem volume was obtained for two counties in Sweden (area: 4235 km^2) using multi-temporal ERS-1/2 coherence data. At a local test site the stand-wise retrieval error was below 10% and estimates were in line with in situ measurements. When comparing against plot, i.e. pixel, level data from the National Forest Inventory, the error was 43%, indicating the necessity of averaging to obtain reasonable estimates [18].

The bulk of the retrieval methodology developed for the two examples reported above was in many aspects similar. A model relating the coherence to the forest GSV in terms of essential decorrelation terms was first trained and then inverted. The main difference was in the training approach. In both cases in situ measurements are needed to calibrate the model, although in the former example their importance is minimal and the model is trained primarily using statistical parameters derived from the histogram of coherence. The availability of more images over Sweden allowed a multi-temporal combination of stem volume estimates from individual images. When only one coherence image is available, classification of growing stock is more realistic. The multi-temporal approach is a key to improve estimates with respect to the single-image case.

The legacy of these experiments served to set up what can be considered the major experiment on retrieving forest growing stock volume with coherence data so far. Within ESA's DRAGON Programme SIBERIA-like maps with 50 m spatial resolution were generated from ERS-1/2 coherence data for Northeast and South China (Fig. 3), covering an area of almost $5 \cdot 10^6$ km^2 and reaching an accuracy above 70 % in terms of forest/non-forest when compared against freely available land-cover products such as GlobCover, AVHRR UMD land cover classification, GLC2000 and the National Land Cover Database (NLCD) product of China. Furthermore, an overall accuracy of 79% in terms of forest GSV using forest GSV inventory data at a small test site in Northeast China has been obtained [27]. With respect to the approach developed in Siberia, the algorithm presented in [28] does not rely on in situ measurements and calibrates the model internally based on coherence statistics for unvegetated and dense forested areas. In case of multi-temporal data, the image with the highest coherence contrast is selected for the retrieval.

Despite the gaps in the coverage, the relevance of the GSV maps for Siberia and China shown in Fig. 2 and 3 is enormous considering that they provide unique information on the GSV at regional level. According to our knowledge, there is no other similar product at 50-m resolution for the mid-1990s based on EO-data.

In [18] it was also shown that a rough estimation of stem volume with only intensity measurements is possible, assuming however that the set of measurements is large (approximately 20). The benefit of multi-temporal combination for retrieving GSV in particular with data where noise can significantly affect the retrieval (e.g. C-band backscatter) has been exploited in the BIOMASAR algorithm [29]. The development of this algorithm builds upon the need of extensive information on carbon stocks from poorly mapped areas with the dual purpose of providing updated information to forest inventories (at regional level) and driving terrestrial biosphere models [6]. The method originally developed for Envisat ASAR ScanSAR data is in theory applicable to other EO multi-temporal datasets (e.g. ALOS PALSAR). The dense temporal sampling of the observations compensates for the weak sensitivity of a backscatter observation to forest GSV, leading to estimates of GSV that are beyond expectations.

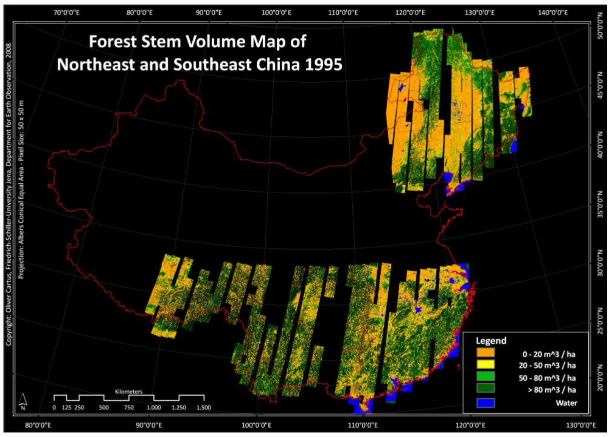

Figure 3. Map of four GSV classes, water bodies and smooth surfaces obtained with multi-seasonal ERS-1/2 tandem coherence for Northeast and Southeast China.

Fig. 4 shows an example of continuous estimates of forest GSV maps for Central Siberia ($2.4 \cdot 10^6$ km^2). The latitudinal gradient of decreasing GSV is well captured. Several experiments carried out in Canada and Eurasia showed a relative RMSE of about 35-40% at the original resolution of the SAR data (100 m and 1 km). Spatial aggregation improved significantly the GSV estimates. Relative RMSE of the order of 20-25% was achieved when aggregating with a factor of 10 (one-dimensional) [29].

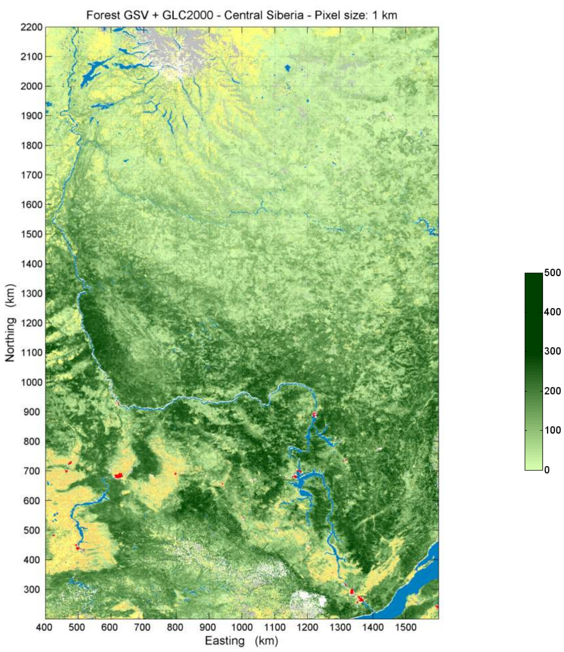

Figure 4. Forest GSV maps of Central Siberia obtained with the BIOMASAR algorithm using a hyper-temporal stacks of Envisat ASAR ScanSAR images. Green shades represent the GSV in m^3/ha. The other color represent non-forest land cover classes, derived from the GLC2000 land cover dataset.

5. FUTURE OUTLOOK

All these investigations demonstrate the capability of currently existing radar data for deriving forest parameters including GSV of the whole northern hemisphere to a level of accuracy sufficient for further exploitation (e.g. carbon accounting) and decision making (e.g. support of Russian forest inventory).

The continuity of the C-band and L-band missions by ESA and JAXA respectively ensures availability of datasets in the future for generation of updated forest cover maps and forest GSV maps as those presented in this paper. ESA's Sentinel-1 and JAXA's ALOS-2 will have improved interferometric features (short repeat-pass intervals). The combination of coherence and intensities at different polarizations is seen as a major advance in terms of accuracy with respect to current capabilities. The use of multi-temporal approaches will also be supported thanks to repeated acquisitions.

Although not treated here, polarimetric interferometry could lead to substantial results once a suitable system will be available in space. A first step in this direction is the forthcoming TerraSAR-X/TanDEM-X constellation, which could serve as a first test of single-pass interferometry to map large areas. Finally, it is important to remark that none of the missions cited so far has been designed for forest applications. The requirement from forest and carbon communities on continuous, accurate and global datasets on forest status and carbon stocks can only be met with dedicated missions. In this respect, it is of crucial importance that missions targeting the observations of forests such as ESA's BIOMASS and NASA's DESDynI are finalized. Integration with less optimal missions, which have already been granted operation though, could further serve to build up a unique observing system for provision of a 3-D representation of forests on a global scale.

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